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LCA FOR ENERGY SYSTEMS

# Parameterized tool for site specific LCAs of wind energy converters

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**Abstract**

*Purpose* The purpose of this project was to provide a parameterized LCA tool that allows performing site specific life cycle assessments for different wind energy converter types by varying a limited number of relevant parameters. Hereby, it addresses the limited transferability of WEC LCA results to other sites as well as the increasing demand for such data.

*Methods* Basis of the work was an extensive primary data collection at the respective production facilities and other relevant stakeholders like site assessment, service etc. Most of the required data was available at first hand and was completed with data from literature and LCA databases. Based on this data, a complex parameterized material flow model has been built and different product variants have been pre-defined within the model, including relevant production processes and upstream. The pre-definition of these product variants allows reducing the minimum number of parameters that need to be configured for site specific LCAs from a total of over 330 to just nine parameters.

*Results and conclusions* In the future, choosing the right type of technology for specific sites will become more important; especially in the face of increasing land use conflicts and increasing competition between renewable energy technologies. Site and technology specific LCAs prove to be a valuable tool for this assessment. Tools like the presented significantly reduce the effort required for performing these LCAs. Additionally, they can be used for various other purposes like environmental assessments of different repowering scenarios and eco design.

**Keywords** Parameterization · Site specific LCA · Transferability · Wind energy

## 1 Introduction

It is well-known and has been shown in various studies (cf. BWE wy 2010; Pick and Wagner 1998; Quaschning 1999; Bunk 2002; Wagner 2004; Briem et al. 2004; Elsam Engineering A/S 2004; Geuder 2004; Mayer-Spohn et al. 2005; Vestas Wind Systems A/S 2006; Crawford 2007; Zimmermann 2011a, b) that wind energy converters (WEC) have the potential to make a major contribution to the attempts of reducing anthropogenic $CO_{2e}$ emissions. At least qualitatively, the environmental and energetic performance looks more or less the same within all these studies: emissions and energy consumption basically arise from the production phase while installation, use, dismantling and disposal contribute less. On the other hand, there is the energy production within the use phase which depends, of course, on the particular site, but usually amounts to a multiple of the cumulated energy demand (CED). This produced energy to CED ratio is also known as the harvest factor.

Besides site specific factors like length of access roads, foundation, coating and other aspects which influence product design and installation and the site specific wind conditions (usually stated in full load hours per year) are decisive for the energetic and environmental performance, e.g. harvest factor and carbon footprint. Values for harvest factors of WEC that can be found or calculated based on literature vary between 20 and 50 (cf. Pick and Wagner 1998; Elsam Engineering A/S 2004; Vestas Wind Systems A/S 2006; Zimmermann 2011a, b). Energetic payback time

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and specific carbon footprint (grams $CO_{2e}$ per kWh) behave likewise. To some extent this might be caused by differing assumptions, system boundaries and actual differences between the assessed converters in terms of their design and production processes. However, it can be assumed that this range is to a large extent due to the impact of the respective site. This means that results from a life cycle assessment (LCA) that has been performed for one particular converter at a specific (or generic) site have only very limited transferability to other sites.

At the same time, there is an increasing demand for carbon balances, energy balances and full LCAs from (potential) operators and policy makers. To address this conflict of demand and validity of available data, a parameterized LCA tool for site specific LCAs (pLCAt) has been developed in cooperation between the department for Technological Design and Development at the University of Bremen and Enercon, the leading German manufacturer of WEC. This tool allows performing site specific LCAs for various implemented converters with significantly reduced effort, among other potential uses.

## 2 Development of the tool

The goal for the development of the tool was to enable the performance of site specific LCAs for different converter types (e.g. E-82 with 2MW, E-70 with 2.3MW, E-82 E2 with 2.3MW) and their respective tower types (77 m steel/ 87 m, 107 m, 137 m pre-cast concrete tower).

The cooperation with Enercon and especially Enercon's very high in-house production depth allowed a very extensive collection of primary data. Data could be collected directly in the manufacturing sites of the various WEC components like rotor blades, generator, nacelle, electronics and tower, meaning that required data about materials, production processes and wastes as well as construction and maintenance had been available at first hand. Questionnaires, statistics, bill of materials and interviews have been used in this process.

Based on the collected data and analyses of the product system a generic inventory model of the life cycle of a wind energy converter has been built, covering all relevant processes and stages of a WEC's life cycle. Where necessary, e.g. for raw material extraction, grid mix and waste treatment, the data had been completed with data from LCA databases (PE and LBP 1999–2008). Figure 1 shows the system boundaries within the tool: They cover raw material extraction, production of the different components and subcomponents, installation, use phase (including service, maintenance and operation), dismantling and end-of-life (EoL) as well as related transport processes and energy supply. As mentioned above, the model was constructed as a generic model, including all processes relevant for the assessed converters in general, but no specific data regarding production (e.g. material amounts, energy consumption), installation (e.g. size of foundation, length of grid connection), transport (e.g. distances, means of transport), use phase (e.g. full load hours, maintenance intensity) and EoL (e.g. recycling rates, re-use of components). This data were fed into the model via parameter settings based on the collected primary data. This way, the required user input is

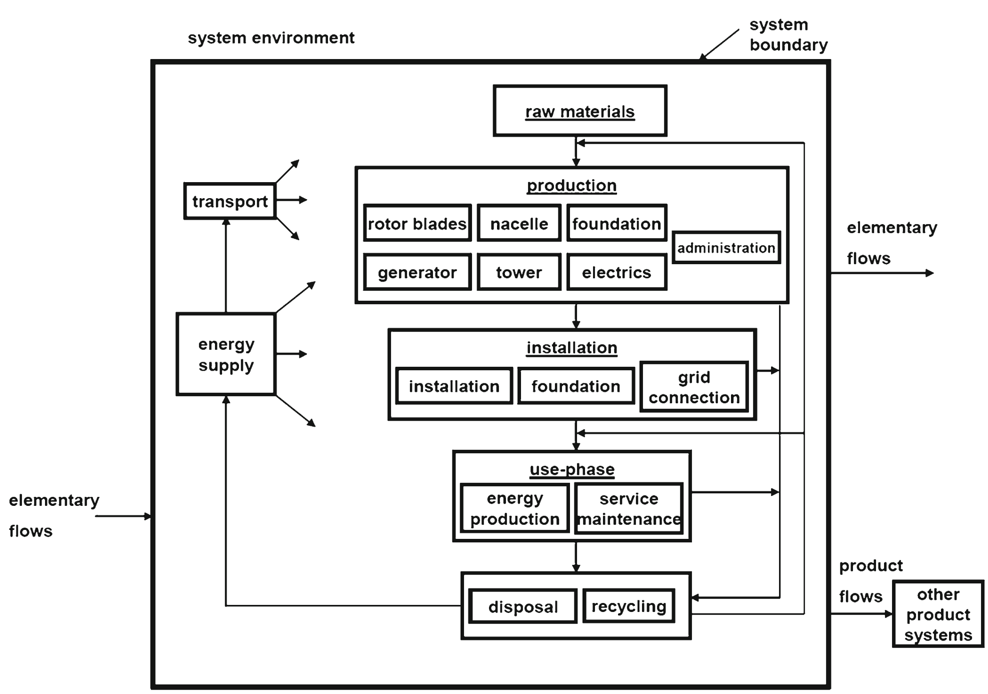


Fig. 1 System boundaries in WEC LCA

reduced significantly to several top-level parameters. This reduction processes is explained in more detailed in the following sections. Besides the top-level parameters, adjusting the "hidden"-parameters in the underlying model provides additional possibilities that go beyond the scope of most LCA studies.

## 2.1 Configuration of production and installation phase

The production phase is mainly determined by converter and tower type. Primary data on amounts of materials, waste and scrap, operating materials, production processes and waste treatment have been collected for each component of the assessed converters and towers, i.e. for rotor blades, generator, nacelle, electrics, tower and foundation. Administration has been included by average values without differentiation between different types of converters and towers.

Based on the collected data, different converter types (e.g. 2MW, 2.3MW, 3MW) and tower types (steel or precast concrete; height) have then been pre-defined in the model using the parameterization of the tool and allowing to select the respective converter/tower combination without requiring input of further parameters for the production stage. A schematic view of this process is given in Fig. 2; an example of (aggregated) inventory data that is the basis pre-defining the parameter setting of the production phase for one particular converter/tower combination (E-82 E2 and 107 m pre-cast concrete tower) is given in Table 1.

Additional product configurations that might vary depending on the specific local requirements like color and type of coating, heating for rotor blades, or lighting systems have only a minor impact on the production phase's LCI (cf. Zimmermann 2011a, b). These aspects have been integrated as average values, just like production logistics (e.g. transportation between the different facilities) and expenditures for heating, lighting and administration. Still, they are available as "hidden parameters" and can be adjusted if needed.

The size of the foundation depends on the respective converter-tower combination as well as on the condition of the soil. Here, average values for each converter-tower combination have been pre-defined and are selected automatically by default. However, they can be adapted if required. The same applies to the lengths of access roads and grid connection. These depend, of course, strongly on the site, but average values (representing a German average), which can be adapted, have been implemented as default settings.

Some other factors, like transport to the site, are to a great extent depending on the location, too. This applies to the transport distance as well as to the means of transport (truck, railway, ship (ocean) and ship (river)). Therefore, these parameters were not pre-defined and need to be configured individually for each assessment. In combination with the selected converter/tower combination and the resulting transport weight, the respective impacts are then being calculated.

Expenditures for the installation itself (e.g. diesel consumption for crane), however, mainly depend on the converter-tower combination (and the resulting weight of the converter) and are configured accordingly. The same applies to dismantling of the converter at the end of its life span. An overview of these parameters and their implementation in the tool is given in Fig. 3.

## 2.2 Configuration of the use phase

The relevant aspects for the use phase of a WEC are

(a) the site specific wind conditions on the site
(b) power consumption of the converter
(c) the maintenance intensity
(d) the life span of the converters

The wind conditions are usually determined within the site assessment for new converters, and for existing converters, they are a figure that should be well-known. In the pLCAt, the wind needs to be defined as the number of full load hours per year; for more generic assessments it is also possible to choose between three pre-settings for average inland, near-coast and coast sites. Besides power generation, the WEC also obtains

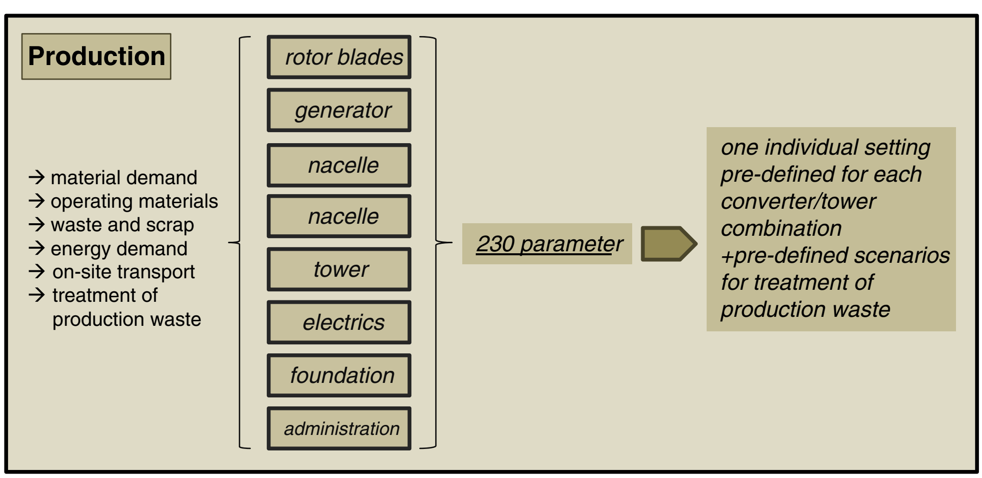


**Fig. 2** Parameter reduction for WEC production

**Table 1** Aggregated inventory data for different production modules of an E-82 E2, 107 m pre-cast concrete tower

| Material | Total [t] | Rotor blades [t] | Nacelle [t] | Tower [t] | Electrics [t] | Foundation [t] |
|---|---|---|---|---|---|---|
| Steels | 246.1 | 1.1 | 53 | 103 | 37 | 52 |
| Cast iron | 73 | | 72.5 | | 0.5 | |
| Copper (w/o cables) | 11 | | 10 | | 1 | |
| Aluminum | 1.28 | 0.08 | 1.2 | | | |
| Glass fibre reinforced plastics | 29 | 29 | | | | |
| Concrete | 1,880 | | | 790 | | 1,090 |
| Total | 2,240.38 | 30.18 | 136.7 | 893 | 38.5 | 1,142 |

power from the grid during the times without sufficient wind for lighting system, adjustment of rotor blades, rotor blade heating etc. This figure is also highly site dependent and needs to be configured via parameters. The default setting of 3,500 kWh/a might serve as a conservative approximation for most state-of-the-art WEC, but if data availability allows it, adapting this parameter is highly recommended.

The service intensity can be configured via two parameters, the number of service trips per year and the distance to the nearest service station. Average data on consumption of spare parts and operating materials provided by the industry partner are used in the tool. The life span of the converters is an aspect with some uncertainty. Here, a realistic assumption of 20 years is the default setting but can be adjusted accordingly. However, most LCA studies on WEC assume a life span of 20 years (cf. d'Souza et al. 2011; Guezuraga et al. 2011; Martínez et al. 2009; Wagner and Epe 2009; Tremeac and Meunier 2009), therefore adaption of the life span should only be performed due to better knowledge; otherwise comparability of the results would be reduced.

An overview of the parameter implementations regarding the use phase is given in Fig. 4.

## 2.3 Configuration of end-of-life

The EoL consists of two different stages that need to be regarded separately. The first stages would be the dismantling of the WEC. Here, the expenditures are defined by the converter and tower type just as for the installation. The other stage of the EoL is the actual EoL treatment of the different components. This phase is characterized by large uncertainties regarding the actual EoL treatment (re-use or recycling; technologies etc.). This uncertainty is partly due to the long life span of WEC and presents an issue that is methodologically challenging. To address this, the tool allows configuring different EoL options:

(a) Cut-off approach: Everything that comes after the dismantling of the WEC is not considered. So, neither the question about the treatment of the EoL components is regarded nor is crediting or allocation an issue.

(b) Reuse of components: For the individual components reuse can be selected (closed-loop). Here, credit is given based on the primary production of these components. In addition to this a correction factor between 0 and 1 may be configured, which allows value correction or distribution of the burdens from the primary production over the life cycles.

(c) Recycling of components: Besides reuse, the individual components can be selected to be recycled. If so, the respective recycling processes are included and system expansion (replacement of primary material) is applied for the produced secondary material. A correction factor between 0 and 1 reflecting the quality losses of the recycled material can be configured here, as well.

The default setting based on primary data and literature sources (PE and LBP 1999–2008; JRC 2010; Worldsteel

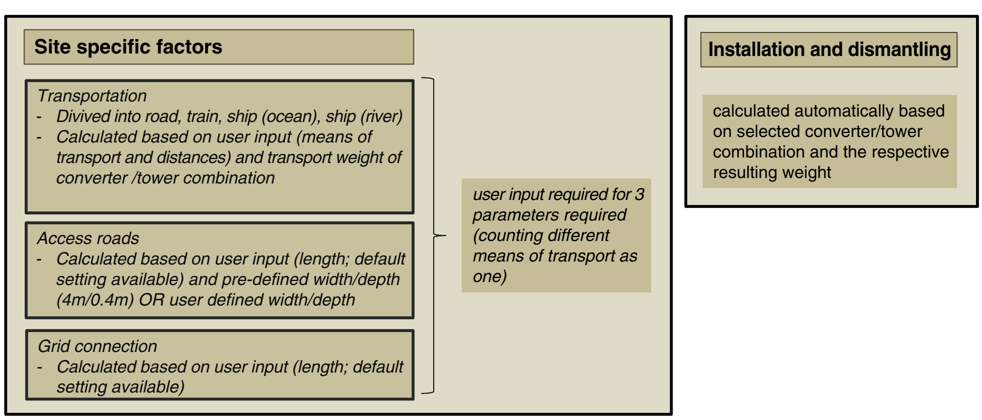


**Fig. 3** Parameter reduction for site specific factors and installation/dismantling

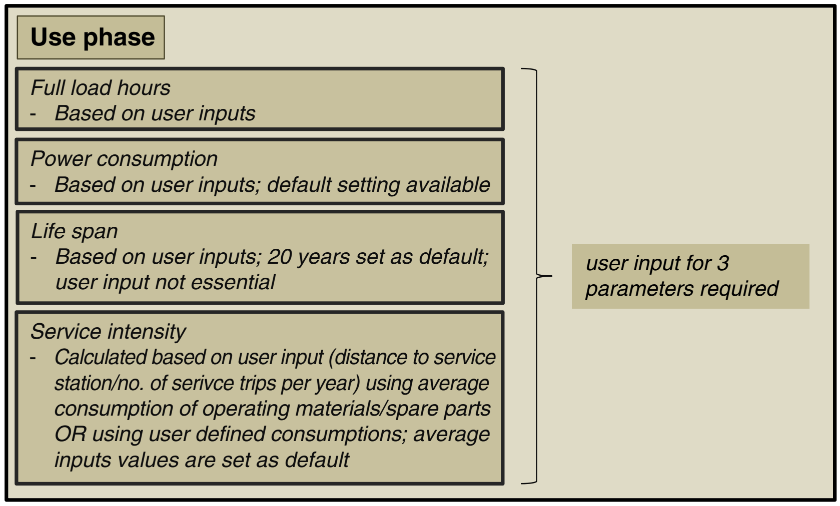


**Fig. 4** Parameter implementation for use phase

2008; VAR 2010; vkn 2010) is shown in Table 2. This setting will be used, if the EoL phase is not configured by the user. The table also includes the default settings for production waste. Besides this default setting, two alternative scenarios can be selected on the top-level of the tool: a scenario with recycling rates that are reduced by 10 % and a scenario that assumes re-use for the WEC as second-hand converter (with exception of rotor blades and tower). Adapting the hidden-parameters in the underlying model offers additional possibilities of configuring end-of-life for each component individually by choosing between recycling and re-use as well as adapting recycling rates and credits granted. A schematic view of the implementation of EoL in the tool is shown in Fig. 5.

**Table 2** Treatment of production and EoL waste

| Material | Treatment |
|---|---|
| Production waste | |
| Household and commercial waste | Incineration with energy recovery |
| Waste oil | 70 % recycling, 30 % incineration |
| Plastics | 80 % recycling, 20 % incineration |
| Steel | 90 % recycling |
| Cast iron | 90 % recycling |
| Aluminum | 95 % recycling |
| Copper | 95 % recycling |
| Other metals | 70 % recycling |
| Wood | Incineration with energy recovery |
| Paper | 80 % recycling, 20 % incineration |
| Electronic waste | Incineration with energy recovery |
| Glass fiber reinforced plastics | Incineration with energy recovery |
| End-of-life waste | |
| Rotor blade | Incineration with energy recovery |
| Tower | Use as filling material, e.g. in road construction (down-cycling) |
| Electronics | Reuse: 60 % for electric components, 93 % for cabinets etc. (Enercon specific figures) |
| Nacelle | |
| - Steel parts | 80 % recycling |
| - Cast iron parts | 80 % recycling |
| - Aluminum parts | 95 % recycling |
| - Copper parts | 95 % recycling |

## 2.4 Top level parameters

As described above, the number of parameters that need user input is reduced from about 330 to nine parameters by implementing parameter pre-settings. The nine top-level parameters shown in Table 3 can be considered as the minimalistic required user input for a site specific LCA.

These parameters can be divided into two groups:

The first group includes converter and tower type, and basically determines the production phase (including raw material production), transportation in terms of the transport weight, installation and dismantling as well as EoL to some extent (depending on the additional settings for EoL). The configuration of the underlying hidden-parameters requires a one-time data collection for each converter and tower type and the implementation of this data into the tool.

The second group, including transport distances, full load hours per year, power consumption, service trips per year and distance to service station, length of access roads and grid connection, includes parameters that are mainly site dependent. These parameters vary from site to site and influence the power generation as well as the environmental impact. An analysis of this impact is presented in the second part of this paper.

## 2.5 Main result figures

Since the entire parameterized model uses full LCA datasets it is possible to choose between various impact categories.

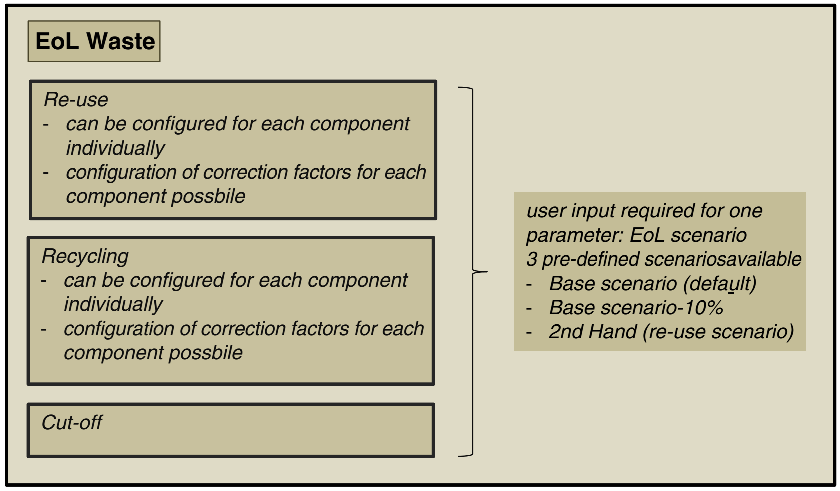


**Fig. 5** Parameter implementation for end-of-life

Nevertheless, the following figures have been identified to be—in most cases—the most relevant figures for wind energy converters:

– Cumulated energy demand (CED)
– Net energy production
– Harvest factor (net energy production/CED)
– Energetic payback time (CED/net energy production per month)
– Global warming potential
– Carbon footprint (grams $CO_{2e}$ per kWh)
– Abiotic depletion potential

The first three indicators represent the converter's energy balance and indicate the converters potential to provide low carbon energy. The global warming potential and the carbon footprint, respectively, are of importance since the reduction of anthropogenic $CO_{2e}$ emissions is one major reason for the promotion of wind energy. The latter indicator addresses the resource intensity of WEC which is an issue of growing relevance, especially with consideration of ongoing discussions regarding the criticality of raw materials. Even though the tool is currently limited to Enercon WEC that do not use neodymium or other rare earth metals, these metals are of increasing relevance within the design of wind energy converters, that might be implemented in the tool eventually, too.

**Table 3** Top-level parameters

| Production and EoL specific parameters<br>Converter type<br>Site specific parameters | Tower type |
|---|---|
| Transport distance | Full load hours per year |
| Power consumption | Service trips per year |
| Distance to service station | Length of access roads |
| Length of grid connection | |

Selected exemplary results are presented in the second part of the paper.

## 3 Selected results and exemplary assessments

The described tool can be used for different purposes. In the following, an exemplary site specific and life cycle wide assessment of an E-82 E2 converter is carried out, followed by a comparison of different product scenarios, a variation of the top-level parameters and an assessment of different end-of-life options. To conclude with, results generated with the tool are compared with figures from literature sources.

The results are partly given as life cycle wide figures, considering all relevant aspects from cradle-to-grave. Additionally, figures like the harvest factor or carbon footprint refer to kWh produced which, here, can be considered as the functional unit.

### 3.1 Exemplary assessments and scenario comparison

As described in the first part, the tool is designed to create site specific LCAs for wind energy converters. To demonstrate this, an assessment of an E-82 E2 with 107 m pre-cast concrete tower at a site with 2,425 full load hours per year has been performed. An overview of the parameter settings for the top-level parameters is given in Table 4. The assessment shows a CED of 3,154.6 MWh, an energetic payback time of about 6.65 months and a harvest factor of about 36. The results can be broken down to the contributions of the different life cycle stages or to component level as it is demonstrated in Figs. 6 and 7 with the CED as impact category. The results for additional impact categories (global warming potential, ozone depletion potential, acidification potential and abiotic depletion potential) are shown in Table 5.

**Table 4** Parameter settings for exemplary assessment (based on Zimmermann 2011a, b)

| Parameter | Configuration |
|---|---|
| Converter | E-82 E2 |
| Tower | 107 m pre-cast concrete tower |
| Full load hours | 2,425 h per year |
| Power consumption | 3,500 kWh per year |
| Transport | 40 km truck, 30 km train, 800 km ship (ocean) |
| Access roads | 150 m |
| Grid connection | 150 m |
| Service intensity | 5 trips per year, 150 km distance to service station |

Additionally to the assessment of a single converter, a tool such as this can be used for scenario comparison, too. It can be assessed, for example, how the environmental performance of different WECs at the same site looks like. This would be an addition for the common economic assessment for the installation of new turbines. Exemplary results are shown in Fig. 8. Here, a 2MW WEC with 107 m precast concrete tower as base scenario (representing 100 %) is compared to a 2MW WEC with 77 m steel tower (and a lower resulting number of annual full load hours; scenario A) and a 2.3MW WEC with 137 m pre-cast concrete tower (scenario B) in terms of their carbon footprint (grams $CO_{2e}$ per kWh), CED and abiotic depletion potential (ADP).

Also, a comparison of one converter (and tower) type at different sites is possible or an assessment of the influence of the number of full load hours on harvest factor and energetic payback time. An example for this is shown is Fig. 9 where the full load hours for one specific converter have been varied (under otherwise equal conditions).

Scenario comparison could also include the comparison of different repowering scenarios, i.e. a comparison of different repowering options under environmental aspects. This possible application has been described in detail in Zimmermann and Gößling-Reisemann (2011). Other possible uses of the tool could be the use as an eco-design and the assessment of complete wind parks, among others.

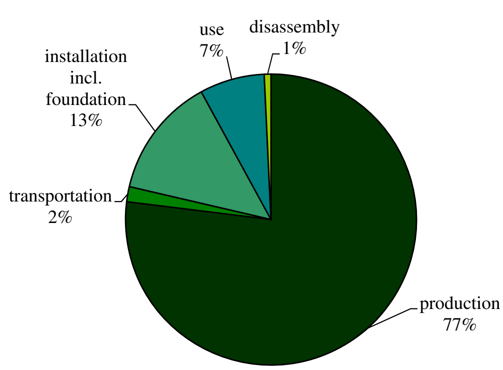


**Fig. 6** Life cycle contributions to the CED

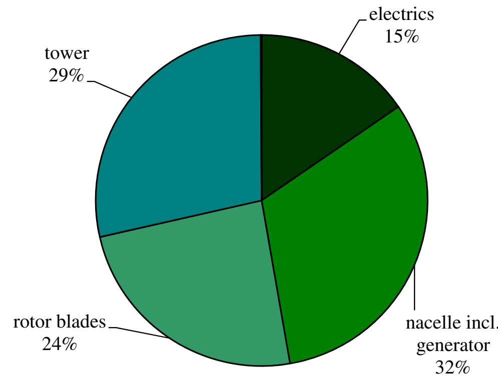


**Fig. 7** Contributions to the CED from different components (in relation to the CED of the production)

## 3.2 Variation of top-level parameters

It was the main objective of the development of this LCA tool to allow the performance of site specific LCAs with significantly reduced effort. To address this, the tool requires—as described above—the configuration of different top-level parameters. To identify the impact of these parameters on the overall environmental performance variation of these parameters has been carried out.

For this assessment the E-82 E2 that has been assessed in the previous section (see Table 4) has been selected as reference scenario, and CED and harvest factor have been chosen as indicators.

Variations of the number of annual full load hours do not influence the CED but lead to rather significant impacts on the harvest factor. This has been demonstrated in the previous section. Within this analysis the number of full load hours has been varied from 2,000 to 3,400. As Fig. 9 shows, this leads to variations of the harvest factor from 30 for 2,000 h/a to over 50 for 3,400 h/a. Additionally, the energetic payback time has been assessed, here, varying from over 8 months for 2,000 h/a to 4.8 months for 3,400 h/a.

The second parameter that is partly dependent on the wind conditions but also on site specific regulations is the power consumption. For sites with constant winds as well as for sites with little regulations regarding lighting and temperatures such that heating of rotor blades is not required, power consumption from the grid will be lower than for sites where these requirements do not apply. To assess this

**Table 5** LCIA results for E-82 E2, 107 m pre-cast concrete tower

| Impact category | Unit | Amount |
|---|---|---|
| Global warming potential | kg $CO_2$-equivalents | 990,000 |
| Ozone depletion potential | kg R11-equivalents | 0.06479 |
| Acidification potential | kg $SO_2$-equivalents | 2,639.5 |
| Abiotic depletion potential | kg Sb-equivalents | 20.6 |

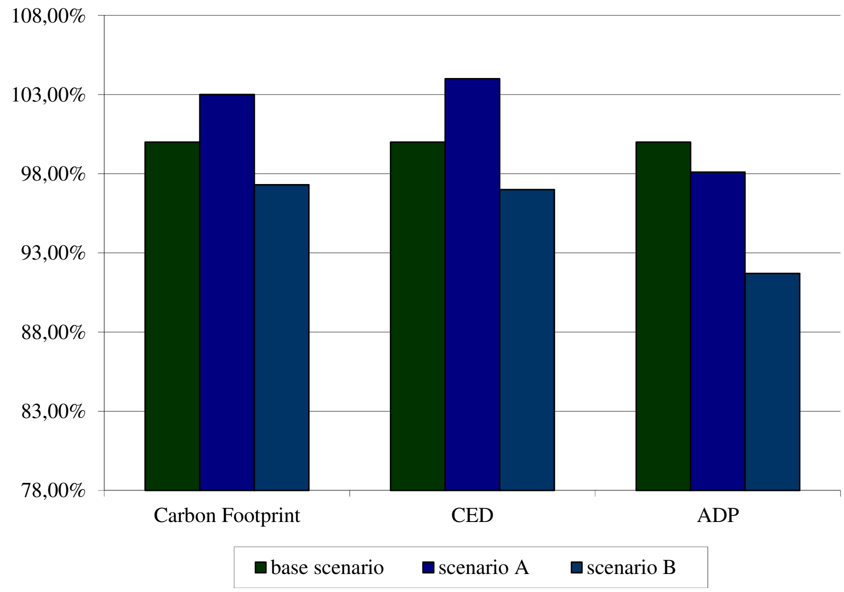


**Fig. 8** Scenario comparison—different product alternatives at the same site in terms of their carbon footprint, CED and ADP

influence the WEC's power consumption has been varied from 800 to 4,000 kWh/a representing a realistic range for the assessed converter type (with 800 kWh/a standing for a site with no need for heating of rotor blades nor lighting systems and only little energy demand for adjustment of rotor blades etc. while 4,000 represents the other extreme). This resulted in variations of the CED from −5.5 % to 1 %.

Depending on the location of the respective site and its distance to the production site different means of transport need to be chosen and different distances need to be covered. Here, four different transportation scenarios have been assessed:

(a) 150 km by truck
(b) 150 km by train
(c) 500 km by truck and 500 km by train
(d) 333 km by truck, 333 km by train and 333 km by ship (inland)

This assessment showed a reduction of the CED of one percent for scenario A and 1.3 % for scenario B, and an increase of the CED of 4.8 % for scenario C and 3.7 % for scenario D.

The lengths of grid connection and access roads can vary within a wide range depending on the individual sites. While for most sites in Germany, for example, access roads with a length of up to one kilometer might be an exception, significantly longer access roads might be necessary for isolated sites in northern Scandinavia. To identify the impact, the parameter has been varied from 0 to 4,000 m for both parameters. This resulted in variations of the CED from −0.6 % to 7.3 % for the access roads and −0.1 % to 0.5 % for the grid connection compared to the reference scenario.

The service intensity is implemented in the model with average consumption of spare parts and operating materials per service trip, i.e. the number of service trips per year and the distance to the nearest service station are the relevant

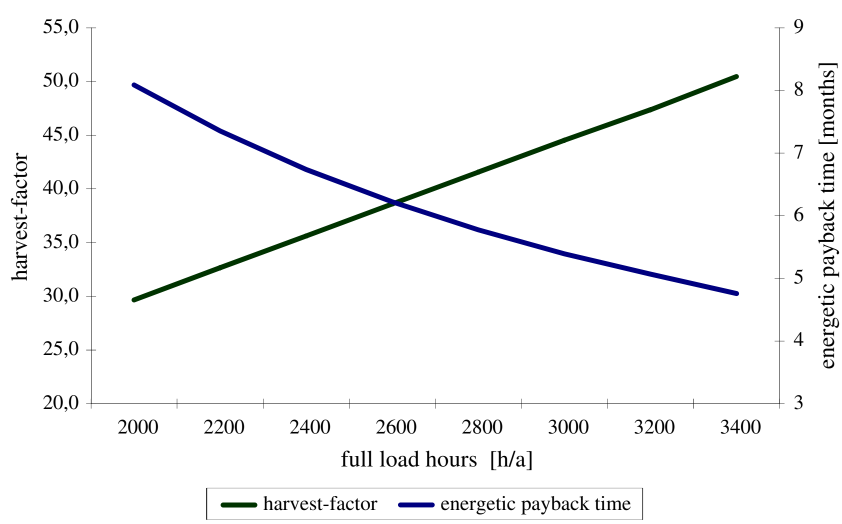


**Fig. 9** Parameter variation—influence of full load hours on harvest factor and energetic payback time

inputs for the service intensity. To assess the impact of variations within the service intensity different service scenario have been analysed. 5, 7 and 10 service trips per year and distances of 150, 300 and 450 km have been assessed. The results of this assessment are given in Table 6. It can be seen that the scenario with the highest service intensity (10 trips per year, 450 km distance to service station) has a CED that is increased by 4.9 % compared to the reference scenario.

### 3.3 EoL scenarios

The tool allows choosing between different end-of-life options. Besides the default setting (recycling according to Table 2) and the alternative pre-settings (recycling rates reduced by 10 % and re-use), other end-of-life options can be assessed. This includes methodological aspects (e.g. choosing between cut-off approach and system expansion; distributing the credit to multiple product systems through “correction factors”) as well as the actual end-of-life treatment (recycling rates for components and materials, re-use of components).

Below, an assessment of different end-of-life options is described, demonstrating the options of the tool as well as indicating differences in the environmental performance. Besides the described base scenario, a scenario with recycling rates that are reduced by 10 % is assessed, a scenario using a cut-off approach, two scenarios assuming re-use of the nacelle and one scenario that assumes re-use of the WEC’s tower with the other settings being equal to the base scenario. For the re-use scenarios, system expansion is used and credits are given using a value correction factor that considers the reduced economic value of the components in their second life. An overview of the scenarios and their differences regarding their CED and GWP is given in Table 7.

It can be seen that methodological aspects as well as assumptions regarding recycling and re-use modeled by system expansion can have a significant influence on the results. Using a cut-off approach increases the CED by 32 % and the GWP by 20 % in the assessed scenario. Assuming re-use of the nacelle while the remaining components are treated the same as in the base scenario reduces the CED by up to 9.5 % and the GWP by 7.4 % respectively. Assuming re-use of the tower segments which is not applied currently but might become an option in the future reduces the CED by 5.7 % and the GWP by 7.6 %.

**Table 6** Assessment of variations in service intensity

| Service intensity (no. trips/distance to service station) | CED |
|---|---|
| 5/150 | 100.00 % |
| 7/150 | 100.40 % |
| 5/300 | 101.00 % |
| 10/150 | 101.00 % |
| 7/300 | 101.80 % |
| 5/450 | 102.00 % |
| 10/300 | 102.90 % |
| 7/450 | 103.10 % |
| 10/450 | 104.90 % |

**Table 7** EoL scenarios for exemplary assessment

| Scenario | Description | CED | GWP |
|---|---|---|---|
| Base scenario | see Table 2 | 100 % | 100 % |
| Cut-off approach | cut-off at EoL | 132 % | 120 % |
| Scenario A | as base scenario, but reduced recycling rates (−10 %) | 105 % | 104 % |
| Scenario B | re-use of nacelle (factor 70 %), including generator (factor 90 %) | 90.5 % | 92.6 % |
| Scenario C | re-use of nacelle (factor 60 %), including generator (factor 80 %) | 93.5 % | 95.3 % |
| Scenario A | re-use of tower (factor 50 %) | 94.3 % | 92.4 % |

### 3.4 Comparison with data from literature

In the following section, the underlying LCI data and results from the tool will be compared with data from literature. It has to be noted, that a comparison such as this has only limited value given the following constraints:

(a) The data in the tool refers to gearless WEC without permanent magnets. Most literature sources refer to WEC with gears that differ in their material consumption.
(b) LCA results are always of limited comparability due to potential differences in the methodological approach and made assumptions. Most literature does not provide sufficient documentation to overcome this constraint.
(c) LCI data from literature is usually only available in an aggregated form, i.e. regarding the product system as a whole. Especially data regarding the site specific factors and material consumptions of the individual WEC components is rarely found.

Given these constraints the following comparison is restricted to serving the purposes of demonstrating that LCI data and results from the tool are within the same range as data found in literature. Aspects (a) and (b), however, could be addressed to some extent by the future implementation of converters from other manufacturers into the tool and performing a greater number of assessments. This would increase the comparability of the results and assessing the validity of the tool’s results would be simplified.

**Table 8** Boundary conditions and results from the tool and literature sources

| Converter/rated power | Reference | Gear (w), no gear (o) | Full load hours [h/a] | CED [MWh] | Harvest factor | Grams $CO_{2e}$/kWh |
|---|---|---|---|---|---|---|
| E-82 E2/2.3MW | Zimmermann 2011b | o | 2,170 | 2,880 | 35.4 | 8.8 |
| E-82 E2/2.3MW | Zimmermann 2011b | o | 2,500 | 2,880 | 40.8 | 7.7 |
| E-82 E2/2.3MW | Zimmermann 2011b | o | 3,100 | 2,880 | 51.0 | 6.1 |
| Vestas V112/3MW | d'Souza et al. 2011 | w | – | – | – | 7.0 |
| 1.8MW WEC | Guezuraga et al. 2011 | o | 1,822 | 2,110 | 31.0 | 8.8 |
| 2.0MW WEC | Guezuraga et al. 2011 | w | 2,990 | 3,910 | 30.6 | 9.7 |
| Vestas V80/2.0MW | Elsam Engineering 2004 | w | 2,825 | 3,625 | 31.2 | – |
| Gamesa G8X/2MW | Martínez et al. 2009 | w | 2,000 | 1,606 | 49.8 | – |
| Nordtank NTK 150/1.5MW | Geuder 2004 | – | 2,450 | 4,404 | 49.5 | – |

Tables 8 and 9 show results and LCI data for an E-82 E2 generated with the tool for different numbers of full load hours. They are compared with converters assessed in different literature sources. As it can be seen from the tables, the results as well as the inventory data vary within a certain range. There are differences in the material consumption which is likely to be due to constructional differences between the different converters. The relatively high copper demand of the assessed E-82 E2 can be explained by Enercon's gearless annular generator concept that uses electro-magnets to induce the magnetic field. However, the high level of aggregation of the data does not allow further conclusions on the reasons for the differences. The figures found in literature for the life cycle wide cumulated energy demand vary from 1,606 MWh for a 2MW WEC assessed by Martínez et al. (2009) to 4,404 MWh for a 1.5MW converter assessed by Geuder (2004). The results created with the tool—a CED of 2,880 MWh—lies within this range. Regarding the differences in the inventory data and given the above constraints, more detailed analyses would be required to identify reasons for these differences.

## 4 Conclusions and discussion

The described tool allows assessing the site influence on the environmental and energetic performance of wind energy converters. After a onetime data collection for each converter and the implementation of this data into the tool, a theoretically infinite number of LCAs can be performed, dissolving the problem of limited transferability of LCA results from one site to another. The required user input for such assessments is reduced from about 330 to nine parameters by pre-defining production settings, considering dependencies between parameters and configuring different EoL scenarios as pre-settings among other means.

As it has been pointed out, the tool allows creating a large number of results and selected scenarios have been assessed exemplarily. The tool allows assessing single converters as well as different scenarios and evaluating them in terms of different impact categories such as the global warming potential, the cumulated energy demand or the abiotic depletion potential. The influence of variations of site-dependent parameters as well as of methodological changes (e.g. means of assessing EoL) can be assessed in doing so.

**Table 9** LCI data from the tool and literature sources

| Converter/rated power | Steel [t] (all types) | (cast) iron [t] | Copper [t] | Aluminum [t] | Glass fiber-reinforced plastics [t] |
|---|---|---|---|---|---|
| E-82 E2/2.3MW | 246.1 | 73.0 | 11.0 | 1.3 | 29.0 |
| Vestas V112/3MW | 245.0 | 65.8 | 5.5 | 6.3 | – |
| 1.8MW WEC | 178.4 | 44.1 | 9.9 | – | 15.0 |
| 2.0MW WEC | 296.4 | 39.4 | 2.4 | – | 34.3 |
| Vestas V80/2.0MW | – | – | – | – | – |
| Gamesa G8X/2MW | 222.5 | 57.5 | 3.5 | – | 8.7 |
| Nordtank NTK 150/1.5MW | – | – | – | – | – |

Regarding the validity of the results calculated with the tool, it can be said that they are in the same range as (static) results from literature. Most LCA studies published in literature, however, do not provide sufficient documentation on how the mentioned site specific aspects are included. Also, constructional changes have, of course, a relevant influence on LCI data and LCIA results, while the level of detail in which inventory data is presented in most studies does not allow any conclusions to the extent of this influence. By implementing data from other industry partners this issue could be addressed.

Regarding the end-of-life stage it has to be noted that the chosen method as well as assumptions can have a significant influence on the LCA results but are usually connected with big uncertainties at the same time. Here, the base scenario offers an approach (recycling + crediting) that is in accordance with literature sources and other LCA studies for WEC (cf. Guezuraga et al. 2011; Martínez et al. 2009; Tremeac and Meunier 2009; Elsam Engineering 2004; Schleisner 2000) as well as literature on the recycling situation of the respective materials and best available techniques (PE and LBP 1999–2008; JRC 2010; Worldsteel 2008; VAR 2010; vkn 2010); hereby a robust approach for assessing the recycling stage is provided that allows evaluating different EoL alternatives, too.

To evaluate the influence that adapting the top-level parameters and hereby rendering the assessment site specific actually has on the LCA results, the respective parameters have been varied with CED and GWP as indicators. For eight of the assessed top-level parameters the CED and GWP varied by at least around 5 %. Only one parameter's variation (length of grid connection) had an impact of less than 0.5 % on the result indicators. This shows the importance of an appropriate configuration of the top-level parameters; in an extreme scenario unfounded assumptions (or insufficient consideration) for transport distances (or means of transport), length of access roads and required service intensity could for example lead to a CED and GWP that are increased by about 15 % compared to the appropriate consideration of these parameters. Also, the relatively low significance of the grid connection parameter is shown. Here, the required user input could be further reduced by implementing a default setting for this parameter based on average values or by linking this parameter, for example, to the length of access roads. However, it has to be noted that within the tool only impacts related to production and installation of the grid connection are considered. Losses occurring due to a longer grid connection are not included at this point. Especially if sites requiring particularly long grid connection and offshore sites (that are currently not within the scope of the tool) shall be assessed, including this aspect should be considered.

Besides the possibilities the tool offers, further developments and extensions could be implemented. These include especially the extension of the present database with additional data from other manufacturers which would add a variety of potential uses. In this context, expanding the tool to offshore converters could be considered. Adding converter types to the tool offers additional possibilities especially regarding the ongoing discussions about the scarcity and criticality of materials. While rare earths are not relevant for Enercon WEC (cf. Enercon GmbH 2011), converters from other manufacturers have an increasing demand for these metals, especially for neodymium for permanent magnets (cf. Angerer et al. 2009; Buchert et al. 2009). Here, the tool could be used to assess different converter types in terms of their resource intensity, using for example the ADP as an indicator. Other potential uses regard the level of producers. Here, environmental assessment tools will become more and more important in the face of growing environmental regulations for new projects. To participate in some tenders providing LCA results is already mandatory which had also been the initial motivation for this project. At the same time, these tools can be used by WEC producers not only for reporting purposes, but for further product optimization (eco-design).

At a higher level such tools can be used for assessments on a larger scale. It could be assessed, for example, how the $CO_2$ balance of wind energy in the grid mix of future scenarios (e.g. 2020, 2030, 2050) looks like considering different technology mixes and expansion scenarios. Also, the environmental aspects of WEC repowering could be assessed as it has been demonstrated in Zimmermann and Gößling-Reisemann (2011). This could also be performed on a country level.

In general, environmental assessment tools like the presented parameterized LCA tool for wind energy converters have numerous potential uses beyond the ones mentioned and exemplarily demonstrated above and can be a valuable support in many endeavors depending on the respective goal and scope.

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